Neutron Interactions with Matter

Radioactivity - Radionuclides - Radiation
8th Multi-Media Training Course with Nuclides.net
(Institute Joszef Stefan, Ljubljana,
13th - 15th September 2006)

Thursday, 14th September 2006

Neutron Interactions with Matter

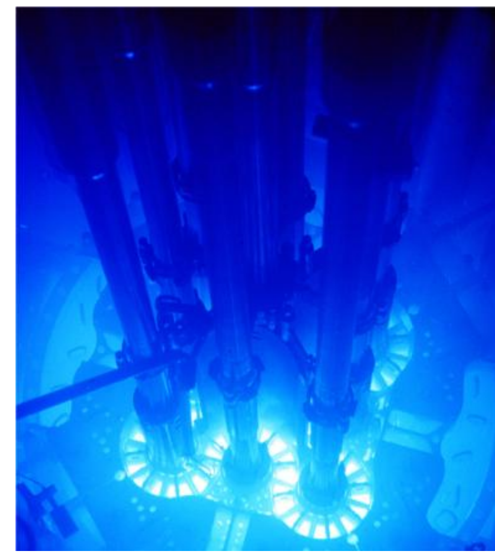
Dr. David Hamilton

European Commission
Institute for Transuranium Elements
Postfach 2340, 76125 Karlsruhe, Germany

E-mail: David.HAMILTON@ec.europa.eu

Why are Neutron Interactions Important?

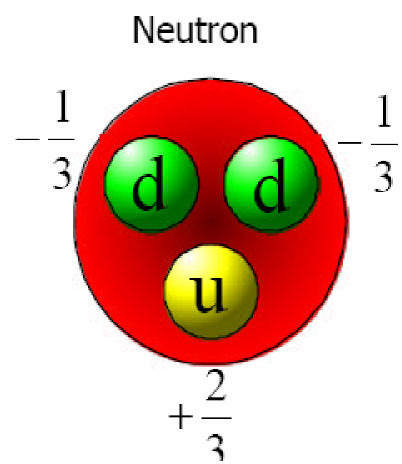
- Common sources of neutrons used in science and industry:
  - Nuclear reactors;
  - Nuclear fusion sources (D-T generators);
  - Accelerator-based sources (spallation);
  - Radioactive decay (^{252}Cf).
- Also produced from other radiation types through secondary nuclear reactions.
- Highly-penetrating, indirectly ionising radiation.
- Can induce large radioactive doses through activation in the body.
- Widely used in nuclear industry, material research, imaging, medical physics ...



ATR, US DoE, Idaho National Lab

The Neutron

- Discovered in 1932 by Chadwick (Cambridge).
- Net Charge = 0
  - very weak electromagnetic interaction, penetrates matter easily, no direct atomic ionisation.
- Mass = 939.56 MeV/c^2
  - slightly heavier than proton.
- Lifetime = 886.7 s
  - free neutrons undergo beta decay
- Magnetic Moment = -1.91 μ_N
  - sensitive to magnetic properties of materials.
- Spin = ½
  - spin-dependent interaction with nucleus.



$$n \rightarrow p + e^- + \bar{\nu}_e$$

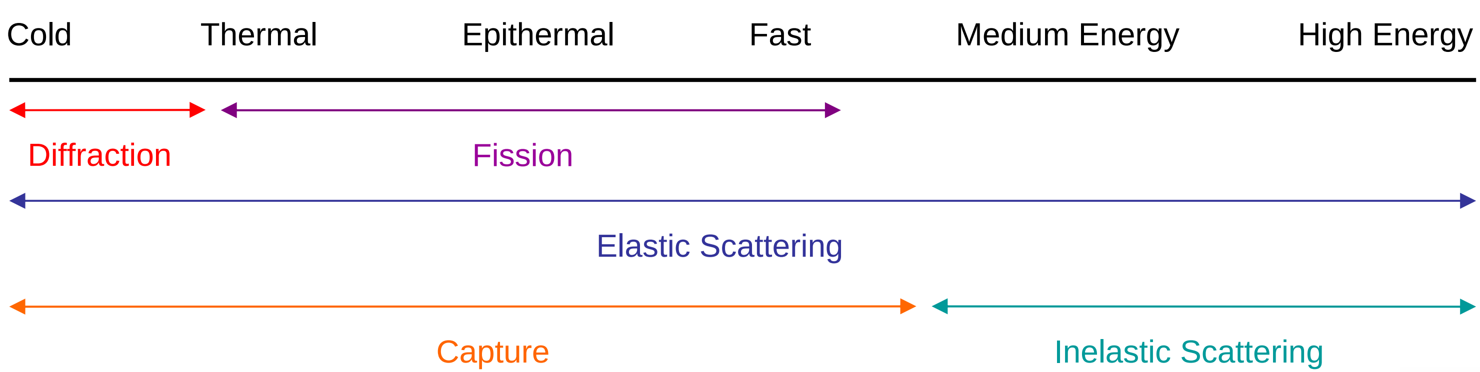
Neutron Interactions with Matter

Neutron Energy Regimes

- Cold < 1 meV
- Thermal < 0.5 eV
- Epithermal 0.5 eV – 50 keV
- Fast > 50 keV
- Medium energy > 1 MeV
- High energy > 10 MeV

Dominant Interactions

- Diffraction
- Elastic Scattering
- Nuclear Reactions:
  - Radiative Capture (n,γ)
  - Other Captures (n,p) or (n,α)
  - Inelastic Scattering (n,x)
  - Nuclear Fission (n,f)



Neutron Interactions with Matter

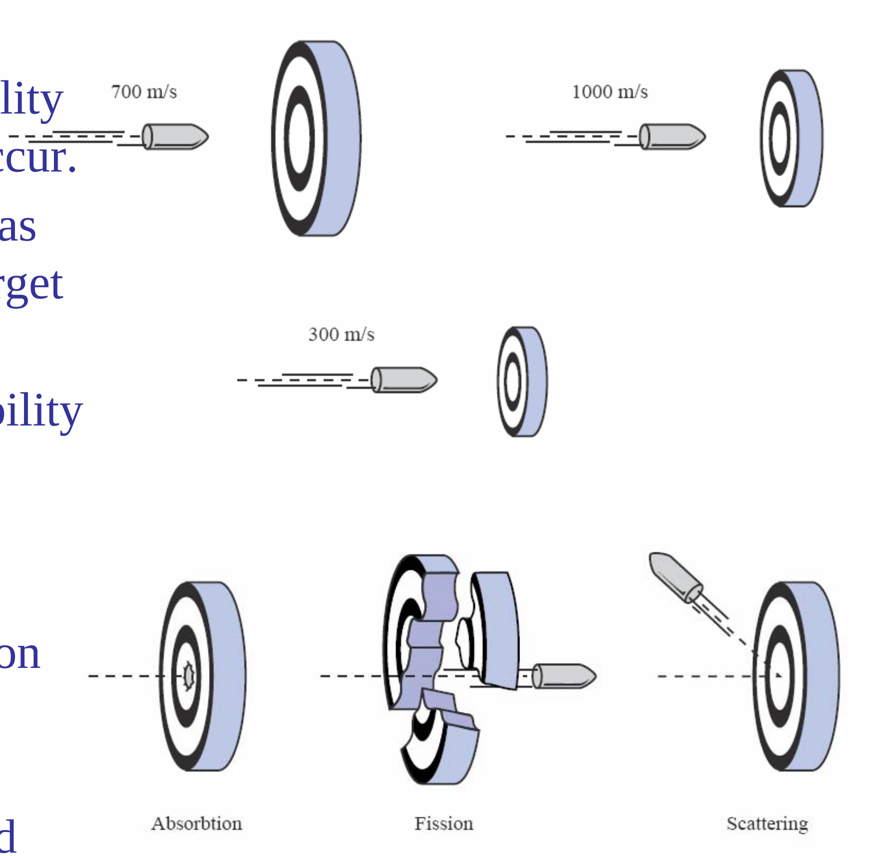
Neutron Interactions: General Characteristics

- In contrast to electrons, photons and heavy charged particles, neutrons undergo extremely weak electromagnetic interactions.
- Neutrons therefore pass through matter largely unimpeded, only interacting with atomic nuclei.
- Even these nuclear reactions have a low probability associated with them.
- This makes neutron transport calculations very difficult; as we are dealing with statistical phenomena, we must resort to Monte Carlo techniques (MCNP).
- In radiation protection, neutron shielding is also not straightforward: one needs to use a material with a high probability of absorbing neutrons (such as concrete, paraffin, borated water or borated polyethylene) .

San Diego Plastics

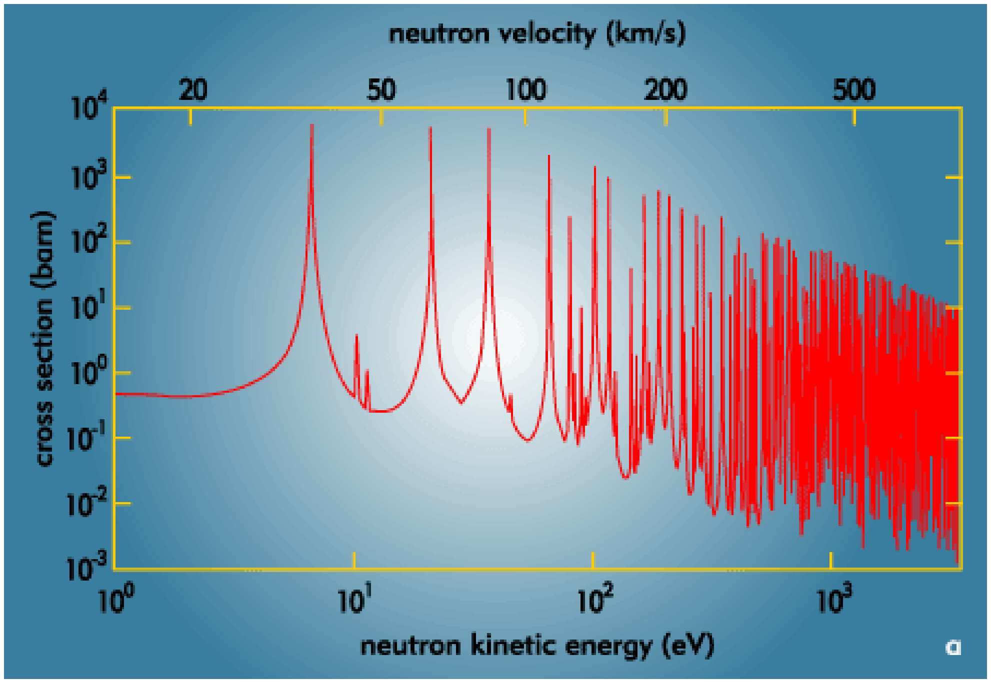
Neutron Cross Sections (I)

- Cross section is a measure of the probability for a reaction between two particles to occur.
- Unit of cross section is the barn, which has the dimensions of area – analogy with target size.
- Microscopic cross section defines probability of **reaction** between neutron and an individual particle or nucleus, i.e. ^{235}U.
- Macroscopic cross section defines probability of **interaction** between neutron and some bulk material, i.e. concrete
- Three most common types of reaction cross sections are **absorption**, **fission** and **scattering**.

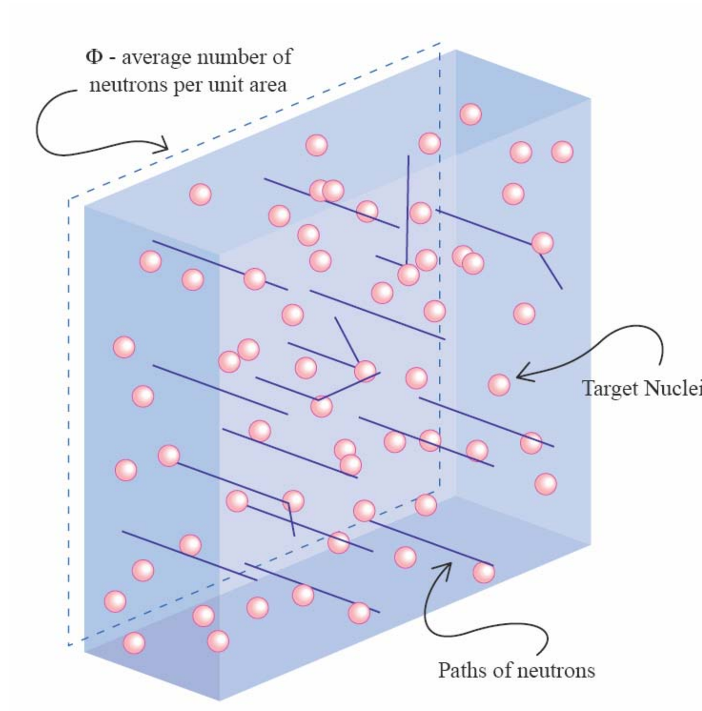


Neutron Interactions with Matter

Neutron Cross Sections (II)



^{238}U Capture Cross Section, CEA



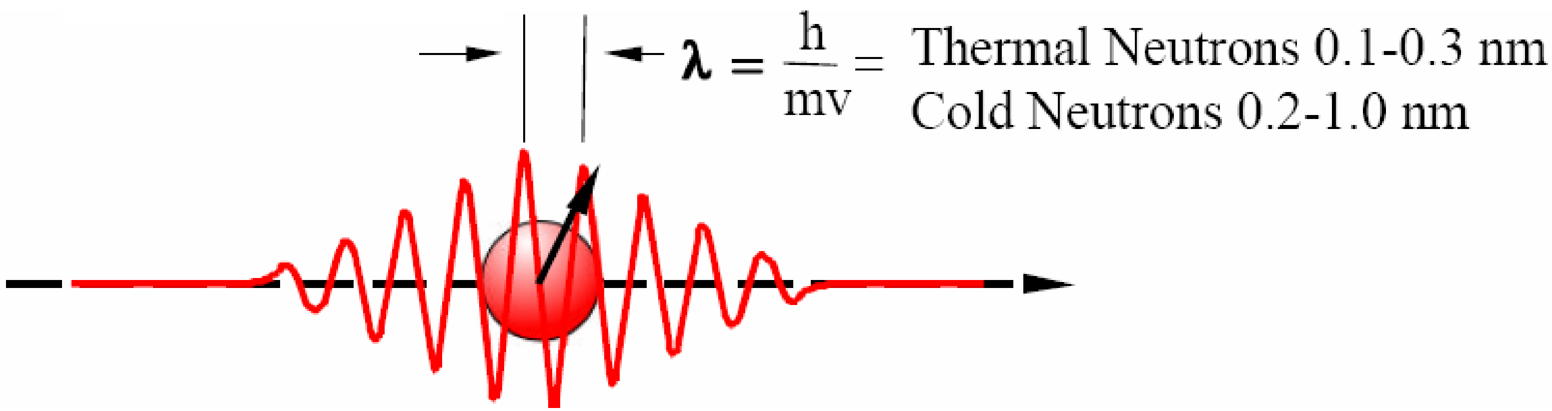
$$\text{neutron reaction rate} = N\Phi\sigma_{ave}$$

- Macroscopic cross section is related to mean free path (λ).
- λ is the average path length in material between two collisions.

Neutron Interactions with Matter

1. Diffraction:
Neutrons as Wave-like Probes of Matter

- Basic quantum mechanics tells us that the neutron exhibits wave-like properties.
- The wavelength is defined by the de Broglie relation.
- Thermal/cold neutrons have wavelengths on the order of crystal lattice spacing.
- Neutrons are therefore a natural complement to X-rays in condensed matter physics. They are sensitive to magnetic distributions, not charge distributions.



MIT Dept. of Nuclear Engineering

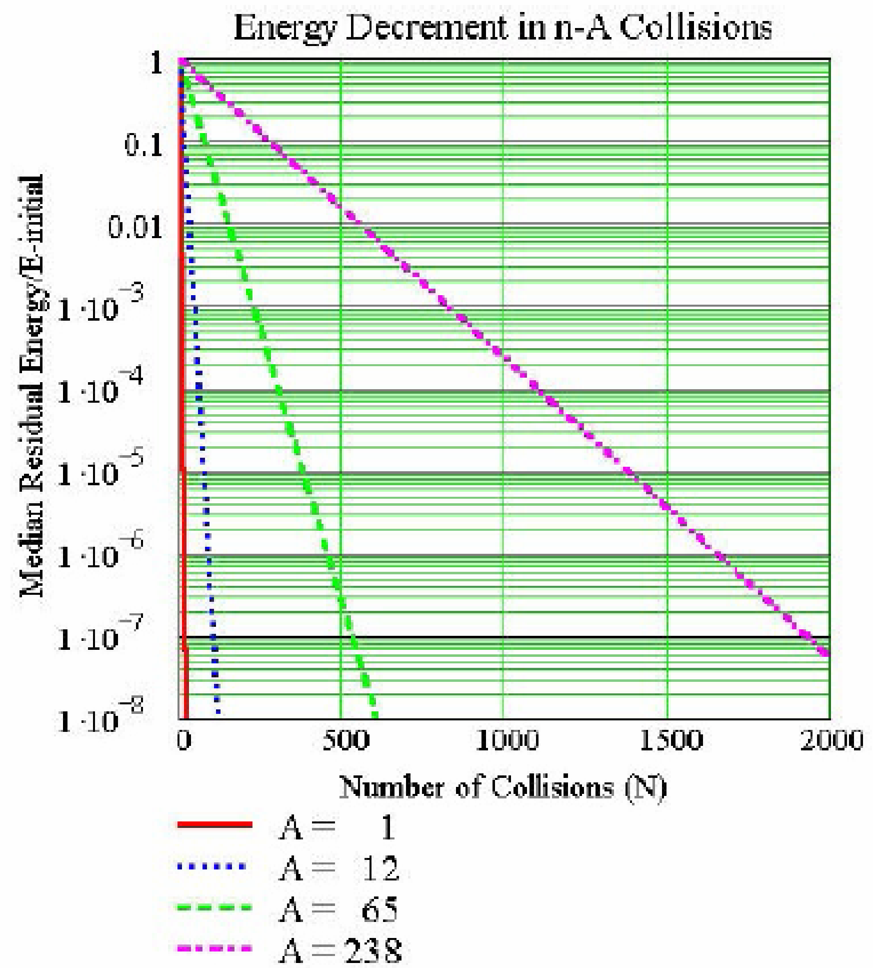
Neutron Interactions with Matter

2. Elastic Neutron-Nucleus Scattering A(n,n)A

- Energy and direction of neutron altered.
- No intermediate excitation of recoil nucleus.
- Dominant energy loss process at intermediate to high energies.
- Process responsible for **Neutron Moderation** (slowing down)

Energy Loss 2 MeV – 0.025 eV:

- A = 1 Ncollisions = 18
- A = 12 Ncollisions = 115
- A = 238 Ncollisions = 2172



Univ. Rochester, Nuclear Science and Technology

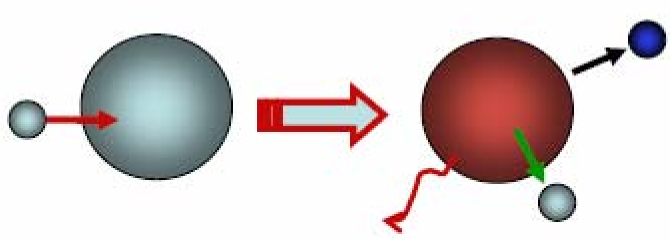
Neutron Interactions with Matter

3. Radiative Capture (n,γ)

- Radiative capture reactions involve absorption of neutrons followed by emission of gamma rays.
- Very important in radiation protection and reactor physics: certain nuclides have very large capture cross sections (resonances) at low energies.
- Therefore, neutron shielding usually includes a material to slow down neutrons and a material to then absorb the slow neutrons.
- Important capture nuclides include Boron, Cadmium and Gadolinium

4. Other Capture Reactions (n,p), (n,α) ...

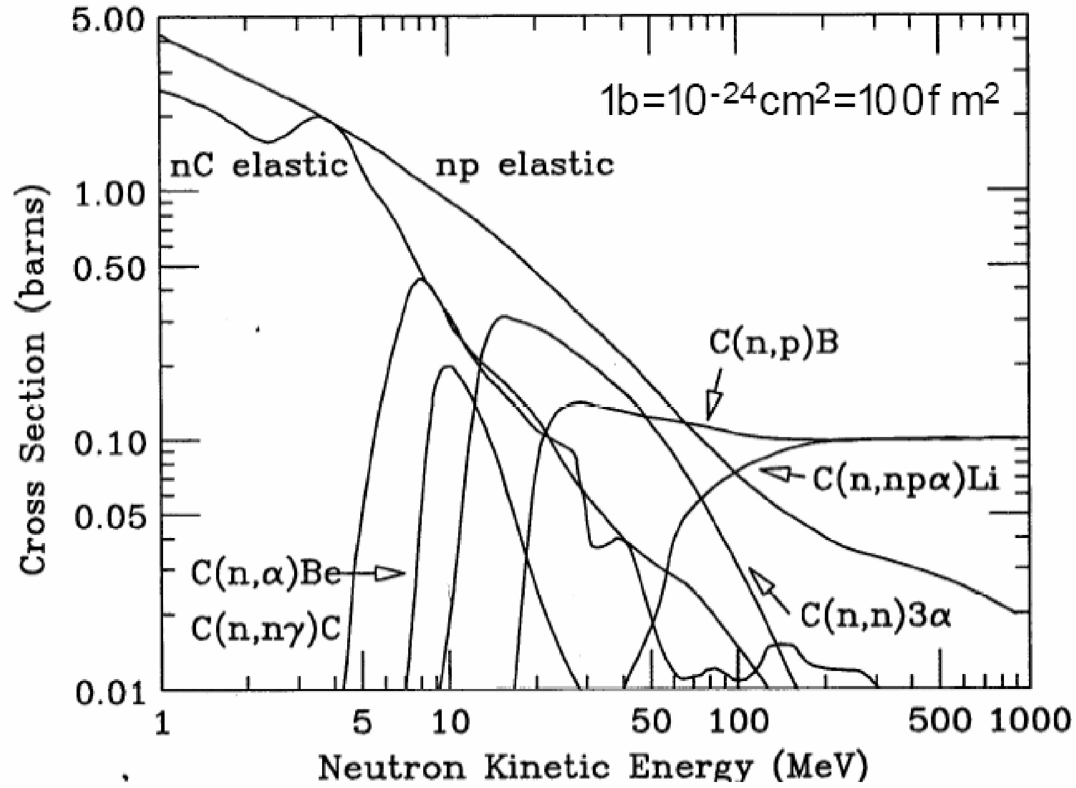
- Other neutron absorption processes exist, such as proton or alpha particle emission.
- Important examples include ^{10}B(n,α) (BNCT) and ^{3}He(n,p) (neutron detection).
- Boron is the most common element added to low Z materials in neutron shielding



Neutron Interactions with Matter

5. Inelastic Scattering A(n,n')A*

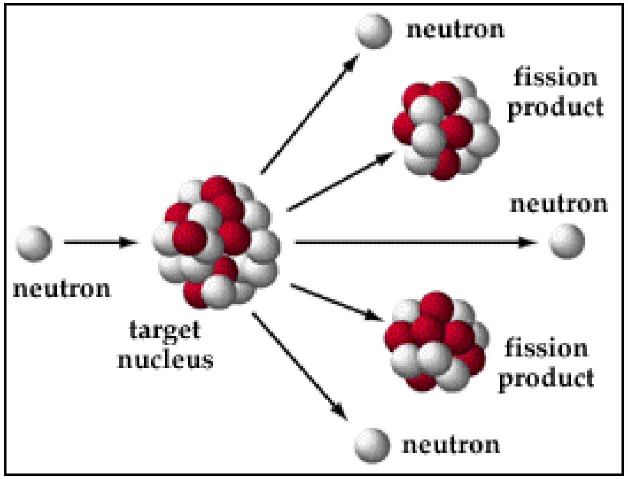
- When neutron-nucleus scattering occurs with neutron energies above several MeV, it becomes possible for the neutron to transfer sufficient energy to the target nucleus to induce an excited nuclear state.
- Neutrons which are inelastically scattered typically lose large fractions of their initial energy, while secondary radiation is produced as the target nucleus returns to its ground state.



Univ. Rochester, Nuclear Science and Technology

6. Neutron Induced Fission (n,f)

- Neutron induced nuclear fission, whereby a heavy nucleus is split into two or more smaller nuclei, was discovered by Hahn, Strassmann, Frisch and Meitner in 1939.
- Because the nuclear binding energies of these smaller nuclei (fission products, with Z around 100) are larger than the binding energies of heavy nuclei, nuclear fission is associated with large releases of energy.
- Many heavy nuclei are fissionable but Uranium, Plutonium and Thorium are the most important fissile nuclides in the nuclear fuel cycle.
- By-products of fission include neutrons, photons and other radiation types. This leads to the concepts of neutron multiplication and chain reaction.
- First sustained chain reaction took place in 1942 in Chicago (CP-1) by a team led by Fermi.
- More on nuclear fission in the next talk ...



Summary

- A neutron radiation field differs in many important respects from "ionising radiation" such as photons, electrons and heavy charged particles.
- These fundamental differences are due to the very weak nature of electromagnetic interactions involving neutrons.
- Neutron interactions are dominated by collisions with nuclei, leading to scattering, capture or fission.
- Neutron shielding and associated calculations are both complicated.
- The health risk associated with neutrons is significant as they are highly penetrating and can induce secondary deep body ionising radiation doses.

Selected Relevant Publications

- J.R. Dunning et al, Interactions of Neutrons with Matter
  Phys. Rev. 48, 265–280 (1935)
- A. Foderaro, The Elements of Neutron Interaction Theory
  MIT Press, Cambridge, USA (1971)
- P. Rinard, Neutron Interactions with Matter
  Los Alamos Technical Report
  http://www.fas.org/sgp/othergov/doe/lanl/lib-www/la-pubs/00326407.pdf
- J. Martin, Physics for Radiation Protection
  John Wiley and Sons, New York, USA (2000)
- Neutron Interactions and Applications, Spring 2005
  MIT OpenCourseWare
  http://ocw.mit.edu/OcwWeb/Nuclear-Engineering/22-106Spring-2005/CourseHome/index.htm